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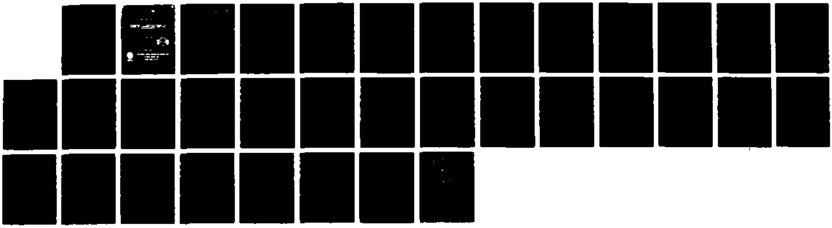

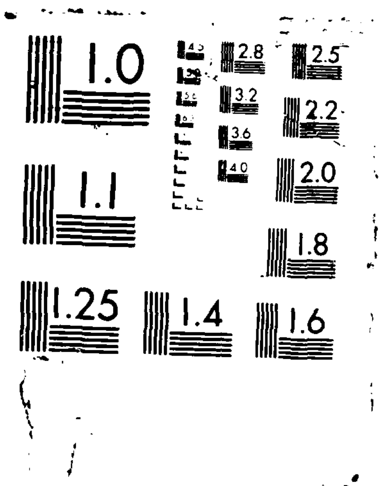
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TECHNICAL REPORT ARFSD-TR-87010

DETERMINATION OF THE COMMUTATION ANGLE AND LOAD RESPONSE FOR A CONTINUOUS-CURRENT, SINGLE PHASE CONTROLLED RECTIFIER

JOHN A. PAPPAS
MAJ JOSEPH E. BENO

MARCH 1988

U. S. ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

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A method has been developed to quantitatively determine the commutation angle and load response for a continuous-current, single-phase controlled rectifier. An analytical model was developed and solved numerically. The results, in the form of load current plots, predict the commutation time and the shape and magnitude of the response. The underlying assumptions used in the development of the model, the limitations of the model, and the interpretation of the results are discussed.

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CONTENTS

FIGURES

INTRODUCTION

Controlled rectifiers employing power semiconductors are used to vary the average power supplied by a constant voltage a.c. source to a load circuit. One of the problems inherent in the design of such a system is the determination of the commutation or overlap angle. Knowledge of the commutation angle gives the designer information about the rate of change of current in the power semiconductor and allows him to accurately model the load current.

A short review of the literature failed to produce a rigorous determination of the commutation angle. Common methods of analysis either ignore the commutation reactance contained in any rectifier circuit or assume constant load current.

The model developed here represents the circuits depicted in figures 1 and 2. A full wave rectifier employing a transformer connected across the single-phase source and a bridge-rectifier circuit are shown in figure 1. The circuit shown in figure 2 also gives full wave rectification and consists of a center-tapped transformer and controlled rectifiers. While the center-tapped transformer has the effect of transforming the single-phase source into a two-phase source, the circuit is commonly referred to as a single-phase transformer.[1]

The load current obtained from either circuit is the same; the choice of which circuit should be employed is application dependant. Factors to be considered in such a selection include cost, required load voltage, and the available voltage supply.[1]

DESCRIPTION OF MODEL AND BOUNDARY CONDITIONS

The method used to calculate the commutation angle and load current is dictated by the fact that no a priori knowledge of the magnitude of the current at the boundaries exits. The current at the boundary points depends on the firing and commutation angles as well as the circuit parameters. As a result, the conventional Laplace transformation approach is not applicable.

---

[1]Dewan, S. B. and Straughen, A., Power Semiconductor Circuits, John Wiley and Sons, New York, 1975, p 216.

To solve the problem, a set of equations with undetermined constants of integration were developed. The equations represent the current in the load during commutation and conduction and the phase "a" current during commutation. Through successive application of the boundary conditions, four independent transcendental equations containing the constants of integration and commutation angle were generated. The equations were then solved simultaneously through an iterative process resulting in numerical values valid for the input circuit values and firing angle.

Continuity of load current was assumed. The method of application of the boundary conditions forces continuous load current and cases resulting in a discontinuous response will not lead to accurate results. Fortunately, it is not difficult to determine if a discontinuous current situation exists. The procedure to determine continuity of current is discussed later.

During the conduction phase of operation, either circuit may be represented by the single phase equivalent shown in figure 3. Since the response of both "phases" to the load is symmetrical, it is only required to calculate the phase "a" response for one half cycle. The response during the second half cycle is simply a time shifted duplication of the phase "a" current.

The commutation circuit (fig. 4) represents the circuit while SCR 1 is coming on and SCR 2 is going off. The voltage sources are sinusoidal so $v_a = V\sin\omega t$ and $v_b = V\sin\omega t$. The time reference is established so that $t = 0$ when the phase "a" voltage becomes positive. SCR 1 is fired at $\omega t = \alpha$. It is assumed that SCR 1 is forward biased at this point. During commutation, both phases conduct simultaneously and the load current, i_d, is the sum of the phase currents i_a and i_b.

The expected load response is illustrated in figure 5. The following boundary conditions used in the formulation of the load current equations are readily apparent from reference to the figure:

$$ia(\alpha) = 0$$

$$id(\alpha + \mu) = ia\ (\alpha + \mu)$$

$$id\ (\alpha + \mu) = iac\ (\alpha + \mu)$$

$$iac\ (\alpha + \pi) - id\ (\alpha)$$

DEVELOPMENT OF EQUATIONS FOR LOAD CURRENT AND CONSTANTS

Beginning with the method described by Hoft[2], the voltage balance around the outside and lower paths in figure 4 is written

$$-V \sin \omega t + L_t \frac{d\,i_a}{dt} + L \frac{d(i_a + i_b)}{dt} + R(i_a + i_b) + V_c = 0$$

$$V \sin \omega t + L_t \frac{d\,i_b}{dt} + L \frac{d(i_a + i_b)}{dt} + R(i_a + i_b) + V_c = 0$$

Adding these two equations and defining a load current during commutation, $i_d = i_a + i_b$, leads to an equation without a forcing term

$$\frac{d\,i_d}{dt} + \frac{2R\,i_d}{L_t + 2L} + \frac{2V_c}{L_t + 2L} = 0 \qquad (1)$$

Equation 1 is a linear first order differential equation and has the solution

$$i_d = k_1 e^{-(t\omega - \alpha)/\omega\tau_1} - \frac{V_c}{R} \qquad (2)$$

where

$$\tau_1 = \frac{L_t + 2L}{2R}$$

and k_1 is to be determined from the boundary conditions. τ_1 is the time constant of the circuit during commutation.

In order to obtain an independent expression for the phase "a" current during commutation, consider the voltage balance around the outer loop of figure 4

$$-V \sin \omega t + L_t \frac{d\,i_a}{dt} + V_0 = 0 \qquad (3)$$

where

$$V_0 = L \frac{d\,i_d}{dt} + R\,i_d + V_c$$

[2]Hoft, R.G., Semiconductor Power Electronics, Van Nostrand Reinhold Co., New York, 1986, p 126.

Taking the derivative of equation 2 and substituting for V_0 and i_d in equation 3 yields a separable differential equation for i_a which can be integrated as

$$i_a \int \left\{ \frac{V}{L_t} \sin\omega t - \frac{k_1}{2\tau_1} e^{-(t\omega - \alpha)/\omega\tau_1} \right\} dt$$

$$= -\frac{V}{\omega L_t} \cos\omega t + \frac{k_1}{2} e^{-(t\omega - \alpha)/\omega\tau_1} + k_2 \tag{4}$$

To determine the constant k_2, apply the first boundary condition ($i_a(\alpha) = 0$) to equation 4. Then,

$$k_2 = \frac{V}{\omega L_t} \cos\alpha - \frac{k_1}{2} \tag{5}$$

Applying the second boundary condition [$i_d(\alpha + \mu) = i_a(\alpha + \mu)$] in equations 2 and 4 and substituting for k_2 from above results in an expression for k_1

$$k_1 = \frac{2}{1 + e^{-\mu/\omega\tau_1}} \left\{ \frac{V}{\omega L_t} \left[\cos\alpha - \cos(\alpha + \mu)\right] + \frac{V_c}{R} \right\} \tag{6}$$

Now consider the conduction period for phase "a" ($\alpha + \mu < \omega t < \alpha + \pi$). Referring to figure 3, the voltage around the circuit can be expressed as

$$-V\sin\omega t + (L_t + L)\frac{d i_{ac}}{dt} + R i_{ac} + V_c = 0$$

The solution for the conduction current is

$$i_{ac} = \frac{V}{Z} \sin(\omega t - \Phi) + k_3 e^{-(\omega t - \alpha - \mu)/\omega\tau_2} - \frac{V_c}{R} \tag{7}$$

where

$$Z = \sqrt{(\omega L)^2 + R^2}, \quad \Phi = \tan^{-1} \frac{\omega(L + L_t)}{R}$$

and

$$\tau_2 = \frac{L_t + L}{R}$$

τ_2 is referred to as the conduction time constant and k_3 is to be determined from the third boundary condition.

The third boundary condition deserves some explanation. Note that $i_d(\alpha + \mu) = i_a(\alpha + \mu) + i_b(\alpha + \mu)$ and $i_b(\alpha + \mu) = 0$. In addition, $i_a(\alpha + \mu) = i_{ac}(\alpha + \mu)$; therefore, $i_d(\alpha + \mu) = i_{ac}(\alpha + \mu)$. Substituting this condition into equations 7 and 2 leads to an expression for k_3

$$k_3 = k_1 e^{-\mu/\omega\tau_1} - \frac{V}{Z} \sin(\alpha + \mu - \Phi) \tag{8}$$

One more independent equation is required to completely specify the four unknowns (k_1, k_2, k_3, and μ). To obtain the last equation, the remaining boundary condition is used. Note first that for steady state operation, $i_{ac}(\alpha + \pi) = i_b(\alpha)$. Using reasoning similar to that above, since $i_a(\alpha) = 0$, $i_{ac}(\alpha + \pi) = i_d(\alpha)$. Using this information in equations 2 and 4 yields

$$k_1 = -\frac{V}{Z} \sin(\alpha - \Phi) + k_3 e^{-(\pi - \mu)/\omega\tau_2} \tag{9}$$

Equations 5, 6, 8, and 9 are four independent equations defining k_1, k_2, k_3, and μ. Substituting equations 6 and 8 into equation 9 yields a single (albeit cumbersome) transcendental equation for μ in terms of circuit parameters. Numerical solution to this equation then allows calculation of k_1, k_2, and k_3. Once these constants are known, i_{ac}, i_d, and i_a can be readily calculated.

DETERMINATION OF MINIMUM PHASE CONTROL ANGLE

As mentioned previously, it is assumed that SCR 1 is forward biased at $\omega t = \alpha$. Once μ is numerically determined, it is a simple matter to check this assumption. Just prior to the instant SCR 1 is fired, Kirchoff's voltage law can be written for the top loop in figure 4

$$-2V \sin\omega t + V_{AK1} - L_l \frac{di_b}{dt} = 0$$

Since $i_a = 0$, $i_b = i_d$ and, using equation 2, the voltage on the SCR is

$$V_{AK1} = -\frac{L_T k_1}{\tau_1} + 2V sin\omega t$$

If V_{AK1} is less than zero, then the assumption was violated and the SCR could not be forwarded biased at $\omega t = \alpha$.[3]

DETERMINATION OF CONTINUITY OF CURRENT

In the previous derivations, it was presumed that operation was under steady-state continuous-current conditions (i.e., i_d is never zero). There are two indicators which can be examined to determine if this assumption is violated.

Some combinations of circuit parameters and firing angle always produce a discontinuous current. These can be determined by assuming a discontinuous current (so there is no commutation) and writing Kirchoff's law for phase "a" conduction

$$V sin\omega t = (L_T + L)\frac{d\, i_a}{dt} + R\, i_a + V_c$$

This equation applies for $\alpha<\omega t<\beta$ where β is the electrical angle at which i_a returns to zero. Solving the voltage equation for i_a and writing $i_a(\omega t = \beta)$ produces a transcendental equation for β.[4]

$$\left\{\frac{E}{R} - \frac{V}{Z} sin\,(\alpha - \Phi)\right\} e^{-R(\alpha - \beta)/\omega L} + \frac{V}{Z}\, sin(\beta - \Phi) - \frac{E}{R} = 0$$

[3]Hoft, R.G., Semiconductor Power Electronics, Van Nostrand Reinhold Co., New York, 1986, p 126.

[4]Dewan, S.B. and Straughen, A., Power Semiconductor Circuits, John Wiley and Sons, New York, 1975, chap. 3.

Since i_a is always positive while SCR 1 conducts, it is not necessary to solve this equation. Subsitution of values for β which are less than the true value will produce a positive number from the above equation, while substitution of values for β which are greater than the true value will produce a negative number. If substitution of the value $\beta = \alpha + \pi$ results in a negative value, then the true β is less than $\alpha + \pi$ and the circuit shuts off completely prior to firing SCR 2. In this case, the current is discontinuous.

The above criterion for discontinuity is not sufficient in all cases. Some cases which pass that test still result in negative values for phase "a" current (indicating a discontinuous case) for some value of ωt between α and $\alpha + \pi$. These cases can only be found by calculating μ and the circuit response for the range of values $\alpha \leq \omega t \leq \alpha + \pi$.

RESULTS

The transcendental equation for μ was solved numerically on a CDC Dual Cyber 170/750. The program (Appendices A and B) allowed input of all circuit parameters and a firing angle, α. The commutation angle, μ, was then calculated using a straightforward method of bisections. If the input α failed the check, as discussed previously, α was incremented by 1 degree and μ was recalculated. This continued until an acceptable α was found (to within 1 degree). The current values were then calculated and plotted. In spite of the unsophisticated method of bisections, run times were relatively short.

The plots from several runs are included which show some trends as various parameters are varied (figs. 6 through 11). The input α for all runs was zero so that the α indicated was the minimum α determined iteratively. In general, large values of inductances were selected to clearly display various trends.

Most runs provided current plots with the expected shapes, even for the flat response expected from a very large load inductance (fig. 10). One run in which the load electromotive force is 50 volts (fig. 11) shows a negative phase "a" current indicating the discontinuous case, which violate our initial assumptions. Therefore, these results are invalid. This case is interesting because it did not have a value of β greater than $\alpha + \pi$.

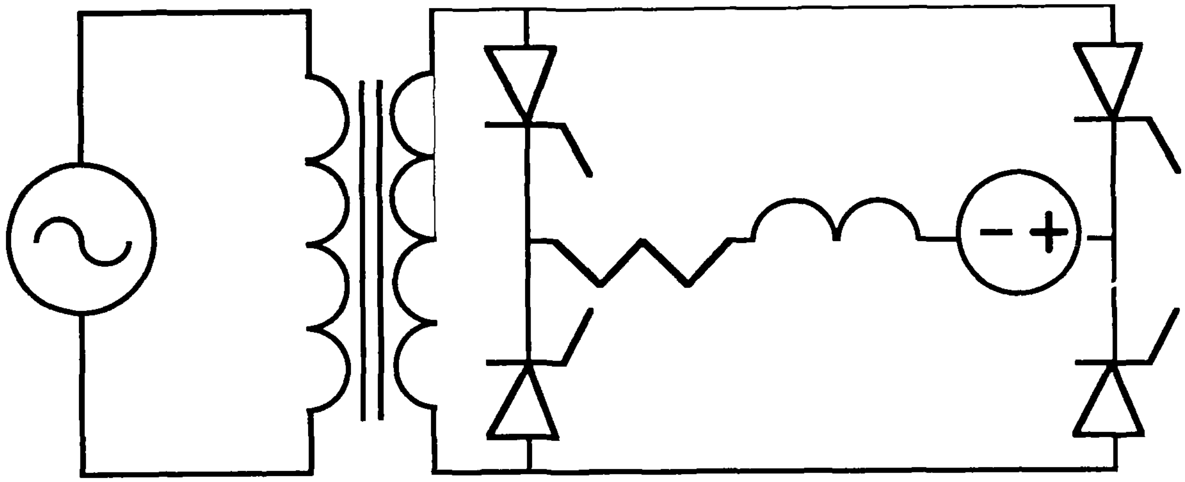


Figure 1. Bridge rectifier

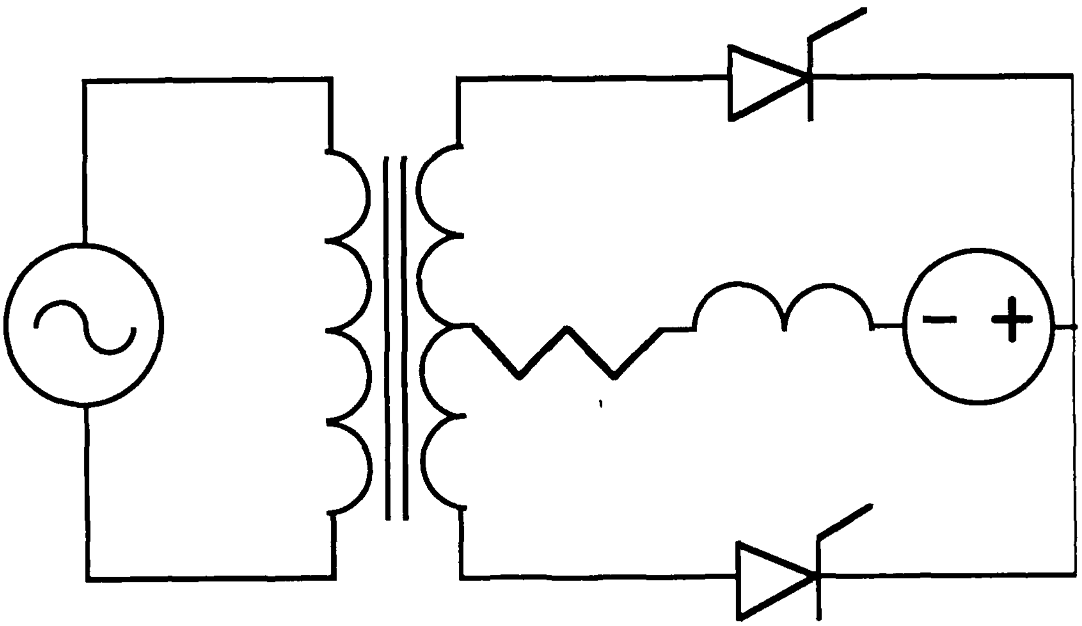


Figure 2. Two-phase rectifier

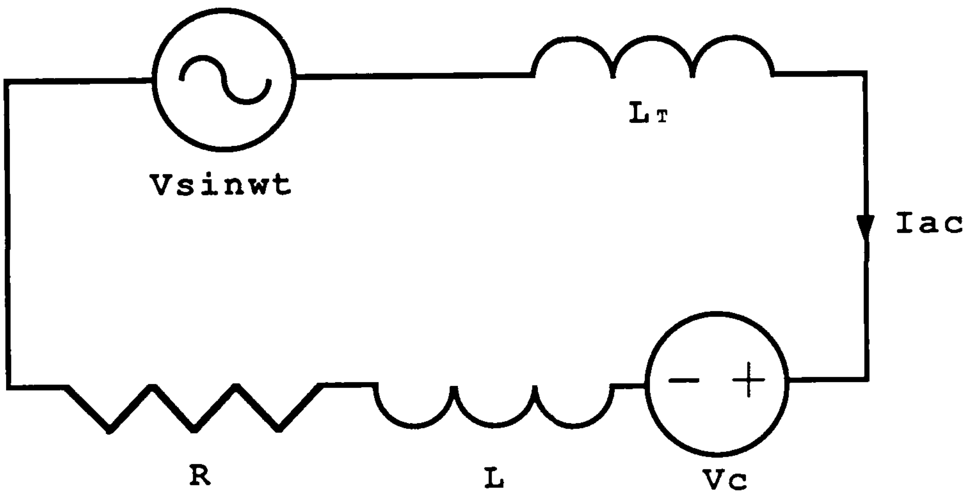


Figure 3. Conduction circuit

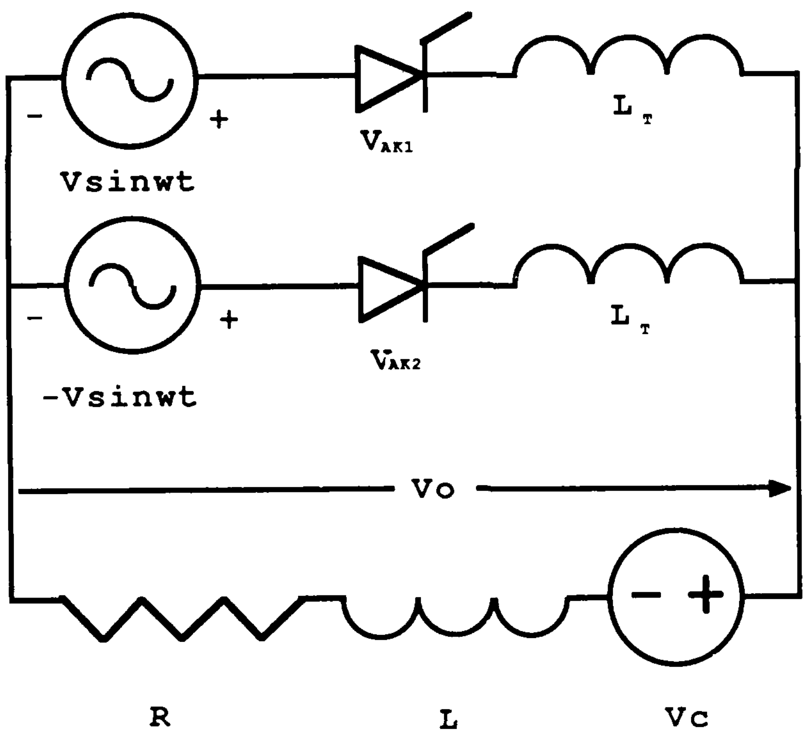


Figure 4. Commutation circuit

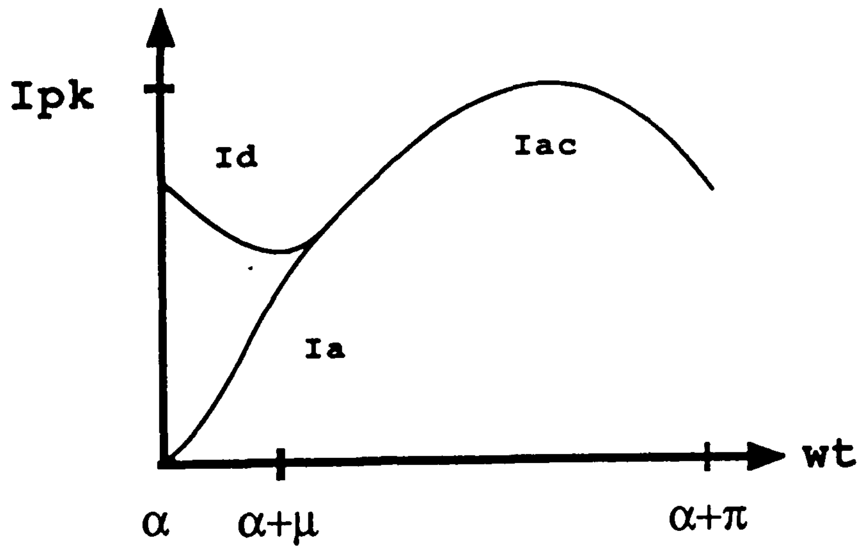
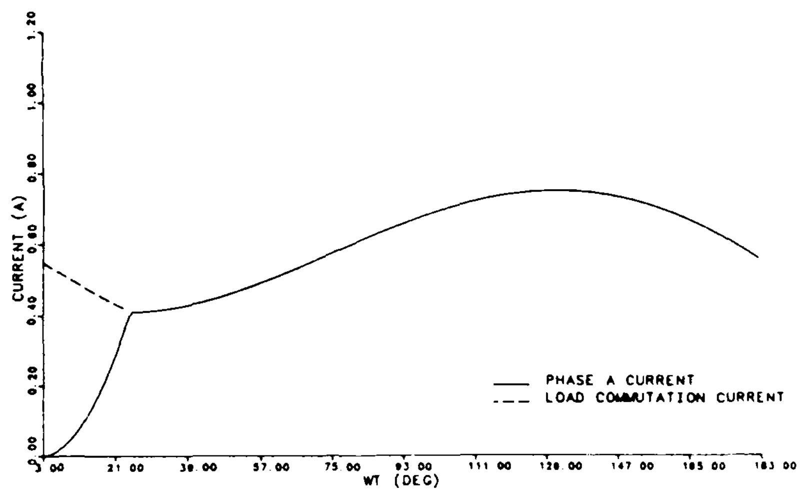
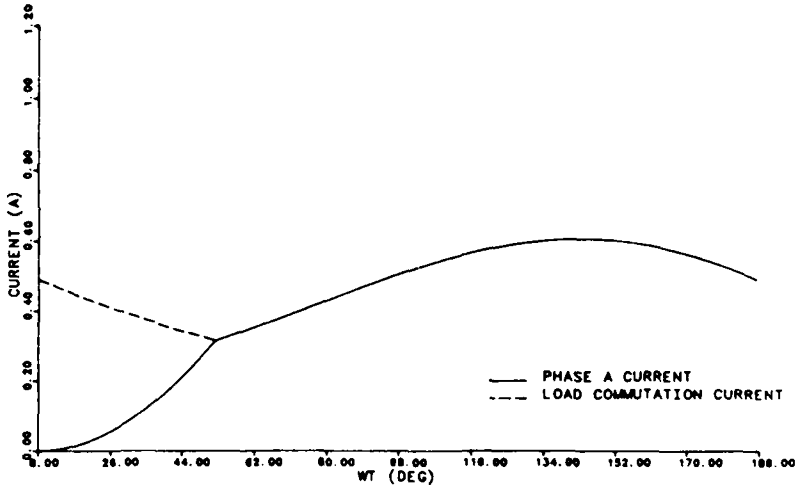


Figure 5. Expected load response



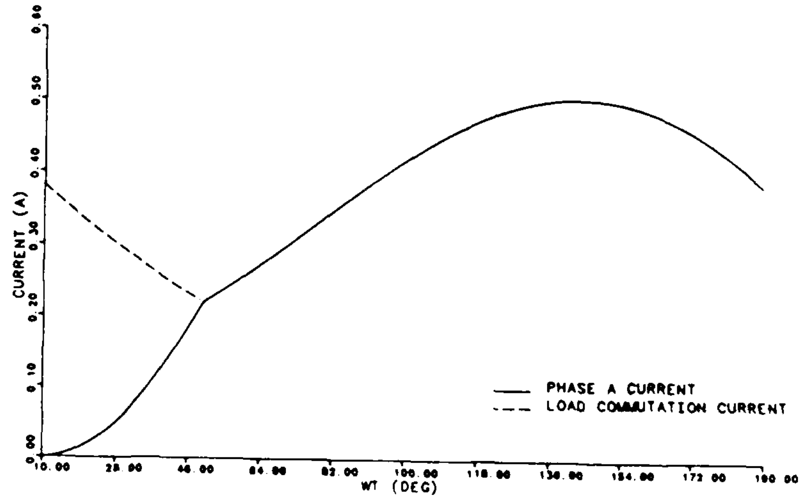
PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60 00	LOAD EMF (V)	0.00
FIRING ANGLE (DEG)	3.00	CONDUCTION TAU (S)	0 0038
TRANS INDUCTANCE (H)	0.0500000	COMMUTATION TAU (S)	0.0035
LOAD INDUCTANCE (H)	0.3260000	COMMUTATION ANG (DEG)	21.7505

Figure 6. Load response for transformer inductance of 50 mH and load inductance of 326 mH



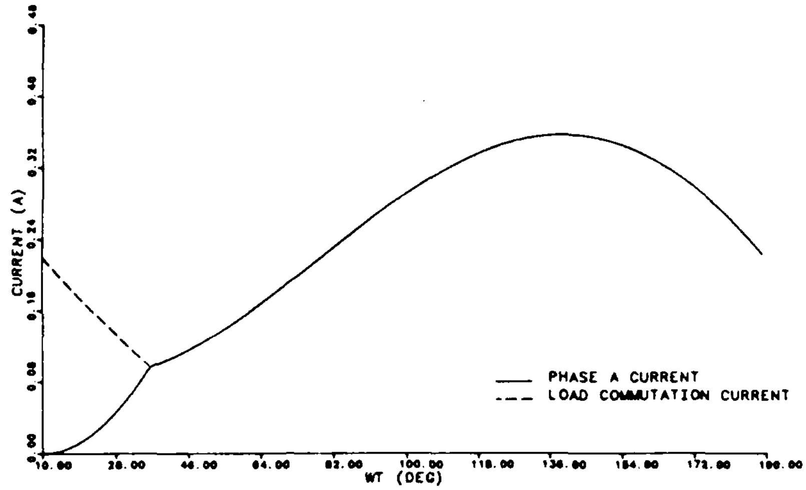
PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	0.00
FIRING ANGLE (DEG)	8.00	CONDUCTION TAU (S)	0.0058
TRANS INDUCTANCE (H)	0.2500000	COMMUTATION TAU (S)	0.0045
LOAD INDUCTANCE (H)	0.3260000	COMMUTATION ANG (DEG)	44.3335

Figure 7. Load response for transformer inductance increased to 250 mH



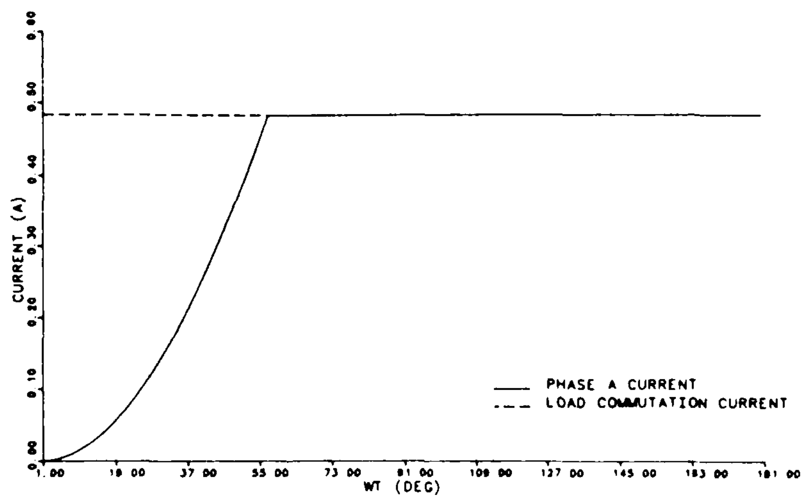
PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	10.00
FIRING ANGLE (DEG)	10.00	CONDUCTION TAU (S)	0.0060
TRANS INDUCTANCE (H)	0.3000000	COMMUTATION TAU (S)	0.0045
LOAD INDUCTANCE (H)	0.3000000	COMMUTATION ANG (DEG)	39.8755

Figure 8. Load response for back EMF of 10 V



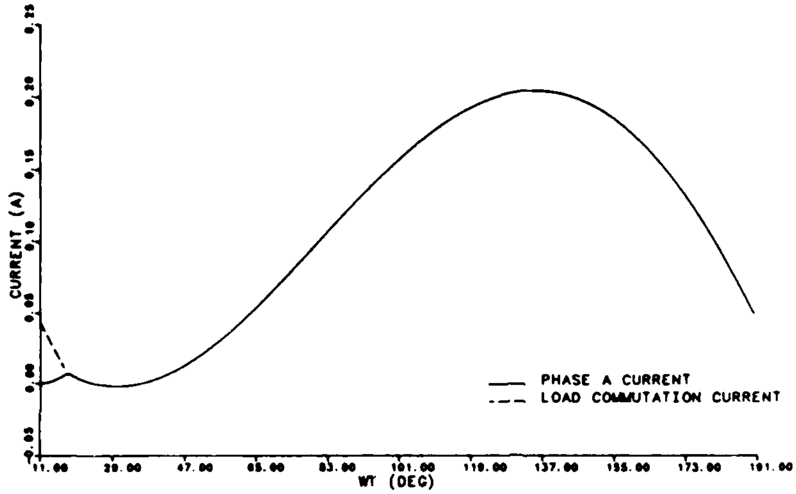
PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	30.00
FIRING ANGLE (DEG)	10.00	CONDUCTION TAU (S)	0.0060
TRANS INDUCTANCE (H)	0.3000000	COMMUTATION TAU (S)	0.0045
LOAD INDUCTANCE (H)	0.3000000	COMMUTATION ANG (DEG)	26.3335

Figure 9. Load response for back EMF increased to 30 V



PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100 00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	0 00
FIRING ANGLE (DEG)	1.00	CONDUCTION TAU (S)	1 0025
TRANS INDUCTANCE (H)	0.2500000	COMMUTATION TAU (S)	1 0013
LOAD INDUCTANCE (H)	100.000000	COMMUTATION ANG (DEG)	56 0005

Figure 10. Flat response for large load inductance



PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	50.00
FIRING ANGLE (DEG)	11.00	CONDUCTION TAU (S)	0.0060
TRANS INDUCTANCE (H)	0.3000000	COMMUTATION TAU (S)	0.0045
LOAD INDUCTANCE (H)	0.3000000	COMMUTATION ANG (DEG)	6.7505

Figure 11. Invalid response showing negative current swing (Current in this case is discontinuous and is not correctly calculated with this model.)

APPENDIX A

FORTRAN SOURCE CODE

```
      PROGRAM SGLFAZ(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7)
*****************************************************
*
*     FORTRAN PROGRAM SINGLE PHASE
*
*     JOHN PAPPAS & JOSEPH BENO
*     UNIVERSITY OF TEXAS AT AUSTIN
*     DEPARTMENT OF COMPUTER AND ELECTRICAL ENGINEERING
*
*     20 APRIL 1987
*
*     COMPUTES THE COMMUTATION ANGLE AND LOAD RESPONSE
*     FOR A SINGLE PHASE FULL-WAVE RECTIFIER.  USER
*     INPUTS ARE LOAD AND SOURCE CHARACTERISTICS, FIRING
*     ANGLE AND TRANSFORMER INDUCTANCE.
*
*****************************************************

*****************************************************
*
*     VARIABLE DICTIONARY
*
*****************************************************

*     A       FIRING ANGLE IN RADIANS
*     ALPHA   FIRING ANGLE IN DEGREES
*     DELTA   TIME-ANGLE INCREMENT IN CURRENT
*             CALCULATION
*     ESIGN   DETERMINES ZERO CROSSING
*             IN MU ESTIMATION ROUTINE
*     EFACT   ACCURACY FACTOR IN METHOD OF
*             BISECTION
*     ENEW    VALUE OF FUNCTION DRIVEN TO ZERO
*             IN MU ESTIMATION
*     EOLD    VALUE OF FUNCTION DRIVEN TO ZERO
*             IN MU ESTIMATION
*     ERROR   NEARNESS TO ZERO REQUIREMENT FOR
*             FUNCTION OF MU IN BISECTION
*     F       SOURCE FREQUENCY IN HERTZ
*     FX      SUBSCRIPTED F (IE. F1, ETC.).
*             HOLDS VALUES GENERATED IN KX
*             ROUTINE
*     ID      LOAD CURRENT DURING COMMUTATION
*     IA      SCR#1 CURRENT DURING COMMUTATION
*     IAC     SCR#1 AND LOAD CURRENT DURING
*             CONDUCTION
*     IAP     ARRAY HOLDING PHASE A CURRENT VALUES
*             FOR ZETA PLOT ROUTINE
*     IDP     ARRAY HOLDING LOAD CURRENT DURING COMMUTATION
*               FOR ZETA PLOT ROUTINE
*     J       COUNTER
*     KX      SINGLE SUBSCRIPTED K.  FUNCTION
*             CONTAINING CONSTANTS OF INTEGRATION
*             IN CURRENT EQUATIONS
*     KXX     DOUBLE SUBSCRIPTED K.  INTERMEDIATE
```

```
*              RESULT
*       L      LOAD INDUCTANCE IN HENRIES
*       LL     TRANSFORMER INDUCTANCE IN HENRIES
*       MU     COMMUTATION ANGLE IN DEGREES
*       MUST   START ESTIMATE OF MU FOR BISECTION
*       MUSTP  STOP ESTIMATE OF MU FOR BISECTION
*       MUOLD  INTERMEDIATE RESULT IN BISECTION
*              USED IN ACCURACY CHECK
*       MUNEW  INTERMEDIATE RESULT IN BISECTION
*              USED IN ACCURACY CHECK
*       PHI    LOAD IMPEDANCE ANGLE IN RADIANS
*       PI     PI
*       R      LOAD RESISTANCE IN OHMS
*       T1     TIME CONSTANT OF COMMUTATION CIRCUIT
*       T2     TIME CONSTANT OF CONDUCTION CIRCUIT
*       TEST1  SIGN DETERMINES SIDE OF ZERO CROSSING
*              IN BISECTION
*       U      COMMUTATION ANGLE IN RADIANS
*       V      PEAK VALUE OF SOURCE IN VOLTS
*       VC     LOAD EMF
*       W      SOURCE FREQUENCY IN R/S
*       WT     INCREMENT ANGLE OF HALF CYCLE
*       WTP    ARRAY HOLDING TIME-ANGLE INFORMATION
*                FOR ZETA PLOT ROUTINE
*       Z      LOAD IMPEDANCE MAGNITUDE IN OHMS


*******************************************************
*
*       HOUSEKEEPING
*
*******************************************************

      REAL L,LL,K11,K12,K13,K1,K41,K42,K43,K44,K4
      REAL MU,K2,K3,MUST,MUSTP,MUOLD,MUNEW,ID,IA,IAC
      REAL IA1,IA2,IA3
      REAL IAP(182),IDP(182),WTP(182)

*******************************************************
*
*      INTERACTIVE DATA ENTRY
*
*******************************************************

  399 FORMAT(//)
  400 FORMAT('INPUT DATA(1) OR USE INTERNAL(0)')
  401 FORMAT('DATA MAY BE INPUT IN REAL,INTEGER OR
     &EXPONENTIAL (XX.XE XX) FORM')
  402 FORMAT('PEAK SOURCE VOLTAGE (V)')
  403 FORMAT('SOURCE FREQUENCY (HZ)')
  404 FORMAT('TRANSFORMER INDUCTANCE (H)')
  405 FORMAT('LOAD INDUCTANCE (H)')
  406 FORMAT('LOAD EMF,VC (V)')
  407 FORMAT('LOAD RESISTANCE (OHM)')
  408 FORMAT('FIRING ANGLE (DEG)')
```

```
409 FORMAT('CONVERGENCE FACTOR (START WITH ABOUT 0.1)')
398 FORMAT('RUN IDENTIFICATION NUMBER')
440 FORMAT('200 ITERATIONS AND STILL THE FUNCTION DOES
   & NOT CONVERGE!')
441 FORMAT('THE ERROR FACTOR CURRENTLY IN USE IS:  ',G18.8)
442 FORMAT('THE "ZERO" YOU ARE TRYING TO MATCH IS:  ',G18.8)
443 FORMAT('THE CLOSEST YOU HAVE COME SO FAR IS:  ',G18.8)
444 FORMAT('INPUT A LARGER ERROR FACTOR')
445 FORMAT('MINIMUM ALPHA REQUIREMENT VIOLATED.')
446 FORMAT('ALPHA INCREASED BY 1 DEGREE TO:',F7.3,'DEGREES')

    WRITE(9,400)
    ACCEPT J
    IF(J.EQ.0)GOTO 10
    WRITE(9,401)
    WRITE(9,399)
    WRITE(9,402)
    ACCEPT V
    WRITE(9,399)
    WRITE(9,403)
    ACCEPT F
    WRITE(9,399)
    WRITE(9,404)
    ACCEPT LL
    WRITE(9,399)
    WRITE(9,405)
    ACCEPT L
    WRITE(9,399)
    WRITE(9,406)
    ACCEPT VC
    WRITE(9,399)
    WRITE(9,407)
    ACCEPT R
    WRITE(9,399)
    WRITE(9,408)
    ACCEPT ALPHA
    WRITE(9,399)
    WRITE(9,409)
    ACCEPT EFACT
    WRITE(9,399)
    WRITE(9,398)
    ACCEPT RUN
    GOTO 20

*****************************************************
*
*    INITIALIZATION AND IDENTIFICATION OF CONSTANTS
*
*****************************************************

 1  EFACT=0.1
    R=100.
    LL=.3
    L=.326
    V=100.
```

```
      VC=0.
      ALPHA=0.
      F=60.
      RUN=100.
   20 WT=0.
      I=1
      ENEW=0.
      MUSTP=0.
      J=0
      T1=(LL+2.*L)/(2.*R)
      T2=(LL+L)/R
      PI=ACOS(-1.)
      W=2*PI*F
      Z=(R**2.+((LL+L)**2.)*(W**2.))**.5
      PHI=ATAN2(W*(LL+L),R)
   30 A=(2.*PI/360.)*ALPHA
      U=0

*******************************************************
*
*    ITERATIVE CALCULATION TO ESTIMATE THE VALUE OF THE
*                 COMMUTATION ANGLE
*
*******************************************************

  110 F1=K1(A,U,T1,W,V,LL,VC,R)
      F3=K3(A,U,T1,W,V,VC,F1,PHI,Z,R)
      E1=2.*VC*T1
      E2=V/Z*SIN(A-PHI)
      E3=F3*EXP(-(PI-U)/(W*T2))
      E4=VC/R
      EOLD=ENEW
      ENEW=E1-F1-E2+E3-E4
      MUST=MUSTP
      MUSTP=U*180./PI
      E=ENEW*EOLD
      ERROR=ABS(ENEW-EOLD)*EFACT
      IF(E.LT.0) GOTO 100
      U=U+PI/180.
      GOTO 110

*******************************************************
*
*     METHOD OF BISECTION TO CALCULATE
*             COMMUTATION ANGLE
*
*******************************************************

  100 MUOLD=MUST
      MU=(MUST+MUSTP)/2.

  120 IF(J.EQ.200)THEN

         J=0
       WRITE(9,399)
```

```
        WRITE(9,440)
        WRITE(9,399)
        WRITE(9,441)EFACT
        WRITE(9,399)
        WRITE(9,442)ERROR
        WRITE(9,399)
        WRITE(9,443)ABS(E)
        WRITE(9,399)
        WRITE(9,444)
        ACCEPT EFACT
        ERROR=ABS(ENEW-EOLD)*EFACT

        ENDIF

       J=J+1
       U=MU*PI/180.
       F1=K1(A,U,T1,W,V,LL,VC,R)
       F3=K3(A,U,T1,W,V,VC,F1,PHI,Z,R)
       E3=F3*EXP(-(PI-U)/(W*T2))
       E=E1-F1-E2+E3-E4

       IF(ABS(E).LE.ERROR)THEN
          GOTO 130
        ENDIF

       TEST1=EOLD*E

       IF (TEST1.LT.0) THEN
          MUNEW=(MU-MUOLD)/2.+MUOLD
        MUOLD=MU
        MU=MUNEW
        GOTO 120
          ENDIF

       MUNEW=(MU-MUOLD)*1.5+MUOLD
       MUOLD=MU
       MU=MUNEW

       GOTO 120

   130 U=MU*PI/180.
       F1=K1(A,U,T1,W,V,LL,VC,R)
       F2=K2(A,T1,W,V,LL,VC,R,F1)
       F3=K3(A,U,T1,W,V,VC,F1,PHI,Z,R)

*******************************************************
*
*      CHECK FOR MINIMUM FIRING ANGLE
*
*******************************************************

       ACHECK=2*V*SIN(A)-(LL*F1)/T1

       IF (ACHECK.LT.0.)THEN
           ALPHA=ALPHA+1
```

```
      WRITE(9,445)
      WRITE(9,446)ALPHA
      GOTO 30
      ENDIF


      CALL OUTPUT(F1,F2,F3,T1,T2,V,VC,LL,L,R,ALPHA
     &,MU,F,EFACT,RUN)

******************************************************
*
*     CALCULATE CURRENT RESPONSE THROUGH COMMUTATION AND
*            ONE CONDUCTION PERIOD  (WT=PI+ALPHA)
*
******************************************************

      WT=A
      DELTA=PI/180.

  140 IDP(I)=F1*EXP(-(WT-A)/(W*T1))-2.*VC*T1
      IA1=V/(W*LL)*COS(WT)
      IA2=(F1/2)*EXP(-(WT-A)/(W*T1))
      IA3=(VC/LL)*(1.-2.*R*T1)*(WT/W)
      IAP(I)=-IA1+IA2-IA3+F2
      WTP(I)=WT
      I=I+1
      WT=WT+DELTA

      IF(WT.LE.A+U)GOTO 140

  150 IAP(I)=(V/Z)*SIN(WT-PHI)+F3*EXP(-(WT-A-U)/
     & (W*T2))-VC/R
      WTP(I)=WT
      I=I+1
      WT=WT+DELTA

      IF(WT.LE.A+PI)GOTO 150

******************************************************
*
*     CREATE PLOT FILE COMPATIBLE WITH ZETA PLOTTER
*
******************************************************
      WTP(181)=A
      WTP(182)=18.
      NPTS=U/DELTA
      NPTS2=180.
      CALL PLOTS(0,0,L"PLOTS")
      CALL ORIGIN(1.0,4.0,0)
      CALL SCALE(IAP,6.,180,1)
      IDP(181)=IAP(181)
      IDP(182)=IAP(182)
      CALL AXIS(0.,0.,'wt',-2,10.,0.,WTP(181),WTP(182))
      CALL AXIS(0.,0.,'Current (A)',11,6.,90.,IAP(181)
```

```
     &,IAP(182))
      CALL LINE(WTP,IAP,NPTS2,1,0,2)
      CALL LINE(WTP,IDP,NPTS,1,O,2)
      CALL PLOT(0.,0.,999)
      STOP
      END

*****************************************************
*
*    DEFINED FUNCTIONS FOR CONSTANTS OF INTEGRATION
*              IN MU AND CURRENT EQUATIONS
*
*****************************************************

      REAL FUNCTION K1(A,U,T1,W,V,LL,VC,R)
      REAL K11,K12,K13,A,U,T1,W,V,LL,VC,R

      K11=2./(1.+EXP(-U/(W*T1)))
      K12=V/(W*LL)*(COS(A)-COS(A+U))
      K13=VC/(W*LL)*U*(1.-2.*R*T1)
      K1=K11*(K12-K13+2.*VC*T1)

      RETURN
      END

      REAL FUNCTION K2  (A,T1,W,V,LL,VC,R,F1)
      REAL A,T1,W,V,LL,VC,R,F1,K21,K22,K23

      K21=V/(W*LL)*COS(A)
      K22=F1/2.
      K23=(VC*A)/(W*LL)*(1.-2.*R*T1)
      K2=K21-K22+K23

      RETURN
      END

      REAL FUNCTION K3  (A,U,T1,W,V,VC,F1,PHI,Z,R)
      REAL A,U,T1,W,V,VC,F1,K31,K32,K34,Z,R,K33

      K31=F1*EXP(-U/(W*T1))
      K32=2.*VC*T1
      K33=VC/R
      K34=V/Z*SIN(A+U-PHI)
      K3=K31-K32+K33-K34

      RETURN
      END

*****************************************************
*
*    SUBROUTINE TO PRINT INPUT DATA AND CALCULATED
*           CONSTANTS TO OUTPUT FILE
*
*****************************************************
```

```
      SUBROUTINE OUTPUT(F1,F2,F3,T1,T2,V,VC,LL,L,R,ALPHA
     &,MU,F,EFACT,RUN)
410  FORMAT(/)
399  FORMAT(//)
411  FORMAT(10X,'INPUT DATA & CALCULATED CONSTANTS FOR
     & PROGRAM SINGLE PHASE')
412  FORMAT(34X,'RUN #',F6.2)
413  FORMAT(10X,'PEAK SOURCE VOLTAGE      ',G18.8,' VOLTS')
414  FORMAT(10X,'SOURCE FREQUENCY         ',G18.8,' HERTZ')
415  FORMAT(10X,'TRANSFORMER INDUCTANCE   ',G18.8,' HENRIES')
416  FORMAT(10X,'FIRING ANGLE             ',G18.8,' DEGREES')
417  FORMAT(10X,'LOAD INDUCTANCE          ',G18.8,' HENRIES')
418  FORMAT(10X,'LOAD RESTANCE            ',G18.8,' OHMS')
419  FORMAT(10X,'LOAD EMF                 ',G18.8,' VOLTS')
420  FORMAT(10X,'COMMUTATION ANGLE        ',G18.8,' DEGREES')
421  FORMAT(10X,'ACCURACY FACTOR          ',G18.8)
422  FORMAT(10X,'COMMUTATION TAU          ',G18.8,' SECONDS')
423  FORMAT(10X,'CONDUCTION TAU           ',G18.8,' SECONDS')
424  FORMAT(10X,'CONSTANTS IN CURRENT EQUATIONS')
425  FORMAT(15X,'K1=',G18.8)
426  FORMAT(15X,'K2=',G18.8)
427  FORMAT(15X,'K3=',G18.8)

     WRITE(7,410)
     WRITE(7,411)
     WRITE(7,412)RUN
     WRITE(7,399)
     WRITE(7,413)V
     WRITE(7,410)
     WRITE(7,414)F
     WRITE(7,410)
     WRITE(7,416)ALPHA
     WRITE(7,410)
     WRITE(7,415)LL
     WRITE(7,410)
     WRITE(7,417)L
     WRITE(7,410)
     WRITE(7,418)R
     WRITE(7,410)
     WRITE(7,419)VC
     WRITE(7,410)
     WRITE(7,422)T1
     WRITE(7,410)
     WRITE(7,423)T2
     WRITE(7,410)
     WRITE(7,420)MU
     WRITE(7,410)
     WRITE(7,421)EFACT
     WRITE(7,399)
     WRITE(7,424)
     WRITE(7,410)
     WRITE(7,425)F1
     WRITE(7,410)
     WRITE(7,426)F2
     WRITE(7,410)
```

```
WRITE(7,427)F3

RETURN
END
```

APPENDIX B

INSTRUCTIONS FOR RUNNING THE FORTRAN PROGRAM

INSTRUCTIONS FOR RUNNING PROGRAM SGLFAZ ON THE UT CDC DUAL CYBER 170/750

Log into your account, then type the commands listed below at the appropriate prompt. User inputs are in **boldface** type.

.READ PF ** **** SGLFAZ**
.FTN5 I=SGLFAZ
.REWALLX
.LDSET LIB=ZETLIBF/
.LGO

**** **** is the access code for the permanent file where the program is stored.

At this point, you will be presented with a choice of using input data contained in the source file or entering your own. If you choose the internal data, the program will run and create the plot and output data files.

If you choose to input your own data, the program will prompt you from the screen. Correct units for the data are indicated with each prompt.

After the program has run, the load response can be plotted. At the prompt type:

.DISPOSE PLOT ID=**

** is the unit identifier for the plotter you are using.

In order to view the input data used and the constants calculated in the program (μ, k_1, k_2, k_3, α, τ_1, and τ_2) on the screen, type:

.SHOW TAPE7

If you want to print the data on a line printer type:

.PRINT TAPE7 ID=**

** is the unit identifier of the line printer you are using.

The file "OUTPUT" contains a compiled listing of the FORTRAN source code.

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